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ABSOLUTE CALIBRATION OF THE FOURIER INTERFEROMETRIC TRANSMISSOMETER

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by

J.-M. Thériault and P.L. Roney

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ABSTRACT

This report presents a detailed analysis of the method used to calibrate the Fourier Interferometric Transmissometer (FIT). Derivation of the calibration equation is based on a fundamental relation of radiometry, the radiance conservation law N' = TN. Thus, the calibrated spectrum of atmospheric transmission is simply determined by obtaining the ratio of a source signal to a local reference signal and then correcting it by the calibration factor. In addition, this report discusses an experimental procedure to evaluate the quality of collimating systems used as a source in transmissometers.

RÉSUMÉ

Ce rapport présente une analyse détaillée de la méthode utilisée pour la calibration du Transmissomètre Interférométrique de Fourier (TIF). La dérivation de l'équation de calibration est basée sur l'utilisation d'une relation fondamentale provenant du domaine de la radiométrie, soit la loi de conservation de la radiation N' = NT. Ainsi, le spectre calibré de transmission atmosphérique est obtenu simplement par le rapport du signal source à celui de la référence locale, rapport qui est ensuite corrigé par le facteur de calibration. De plus, ce document discute une procédure expérimentale conçue spécifiquement pour évaluer la qualité des systèmes de collimation utilisés en tant que sources dans les transmissomètres.

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LIST OF SYMBOLS

A_{ap}	area of field-limiting aperture
A_b	effective area of blackbody
A_b'	area of image of distant blackbody alone
A_d	area of image of distant source
A_m	effective area of mirror
A_m'	effective image area of mirror
d	distance transmitter to receiver
D_{mir}	diameter of distant source mirror
f_1	focal length of receiver telescope
f_2	focal length of interferometer collimator
f_3	focal length of condenser
F_1	position of the distant source image at receiver primary focus
F_2	position of source image at exit aperture (detector)
h_d	diameter of image
$K(\lambda)$	calibration factor

N	object radiance
N'	image radiance
N'_b	image radiance of distant blackbody alone
N'_{loc}	image radiance of local source
N_{loc}	radiance of local blackbody source
N_{mb}	radiance of blackbody mirror source
N'_{mb}	image radiance of distant source assembly
P_b	power (watts) at detector of distant blackbody alone
P_{loc}	power of local source
P_{mb}	power at detector of distant blackbody assembly
P_d	power of distant source
Q	quality factor
R	reflectance of mirrors
T	transmission
T_{atm}	atmospheric transmission
T_{sys}	transmission of system (from F_1 to F_2)

τ temperature of blackbody source

λ wavelength

Ω_{sys} solid angle subtended at the image by the system optical aperture

1.0 INTRODUCTION

The design and the ultimate performance of many electro-optical systems used in defence applications can be strongly affected by atmospheric conditions. Some of the most important factors include molecular absorption, scattering by aerosols, turbulence and refractive index effects. Even if these considerations are not taken into account during the design stage of a system, it is often required to predict the performance under special limiting conditions. One method of estimating the performance under various atmospheric conditions, and which eliminates costly extensive trials, involves the use of atmospheric transmission models. Although transmission models such as the well-known LOWTRAN and FASCODE codes can be used to obtain estimates of the performance of both passive and active systems, it is not always easy to decide which code is the most appropriate or accurate.

In order to be able to make a quantitative evaluation of the accuracy and applicability of such models, it is necessary to have a data bank of accurate measurements of high spectral resolution transmission at long paths and over a wide range of atmospheric conditions. High-resolution spectroscopic transmittance measurements have been performed by the US Naval Research Laboratories over a 5.1-km path for a limited range of atmospheric conditions (Ref. 1). Measurements at low resolution have been performed over a 40-km path (Ref. 2). Further measurements are required, which will include the atmospheric conditions for less temperate climates.

Defence Research Establishment Valcartier (DREV) has set up a 5.7-km transmission range which includes a high-resolution Fourier transform spectrometer system and an infrared source, both designed by Bomem Inc. under contract. The transmission system is referred to as the Fourier Interferometric Transmissometer (FIT). The range will be

used, amongst other applications, to measure atmospheric transmittance under the wide range of atmospheric conditions of temperature, humidity and precipitation in the Quebec City region.

By far the most critical and difficult part of transmittance measurements, either radiometric or spectrometric, is the calibration of the system in absolute terms. Although simple in theory, calibration of the source-receiver system involves many difficulties and potential errors. Each system requires an approach which depends on its optical characteristics. In fact, the system should be designed around a calibration technique rather than the converse. This is not always possible because of cost considerations, which is the case with the DREV system where a strong large source was necessary for the 5.7-km pathlength. The 60-in-diameter transmission source mirror was selected because of its availability and low cost rather than the quality of its optics. It is therefore necessary to be particularly careful in the design of a calibration technique for the FIT system. This report addresses this problem.

Chapter 2.0 gives a brief description of the FIT system. Chapter 3.0 presents a calibration technique which takes into account the quality of the source mirror optics by determining a quality factor. A technique devised for the determination of this quality factor as well as preliminary results are discussed in Chapter 4.0. Finally, conclusions are drawn regarding the factors which affect the precision of the technique, and an estimate is made of the attainable accuracy.

This work was performed at DREV between June 1986 and August 1987 under PCN 33B12, Long-Range Transmission Studies for EO Battleground Surveillance.

2.0 DESCRIPTION OF THE TRANSMISSOMETER

The Fourier Interferometric Transmissometer (FIT) is a device designed to measure transmittance over long atmospheric paths in the infrared part of the electro-magnetic spectrum. The FIT consists of a transmitter and a receiver assembly. A full description of the system may be found in Ref. 3.

Schematic diagrams of the transmitter and receiver optics are shown in Figs. 1 and 2. The transmitter consists of a 60-in diameter parabolic mirror (f=25.5 in) and a 2-in square flat-plate blackbody source. The source is placed near the mirror focus, producing a collimated beam directed at the receiver.

The receiver is made up of a Bomem DA2 interferometer, a Newtonian telescope to collect radiation coming from the distant source (transmitter) and a local reference blackbody source. The telescope has a 17-in diameter primary mirror. The reference source is a cone-type commercial blackbody and is used to calibrate the system. The distance between the remote source and receiver is 5.7 km. The spectral range of the interferometer, using a CaF_2 beam splitter, is 2 to 5 μm (2000-5000 cm^{-1}).

The interferometer can accept radiation from either the distant source or the local source which is contained in the receiver assembly. Ideally, spectra obtained from these two sources would simply be ratioed to yield the transmittance over the atmospheric path that separates them. However, in practice, the signal reaching the detector of the interferometer is affected by several factors. Atmospheric transmittance is determined by obtaining the ratio described above and subsequently correcting it by a calibration factor.

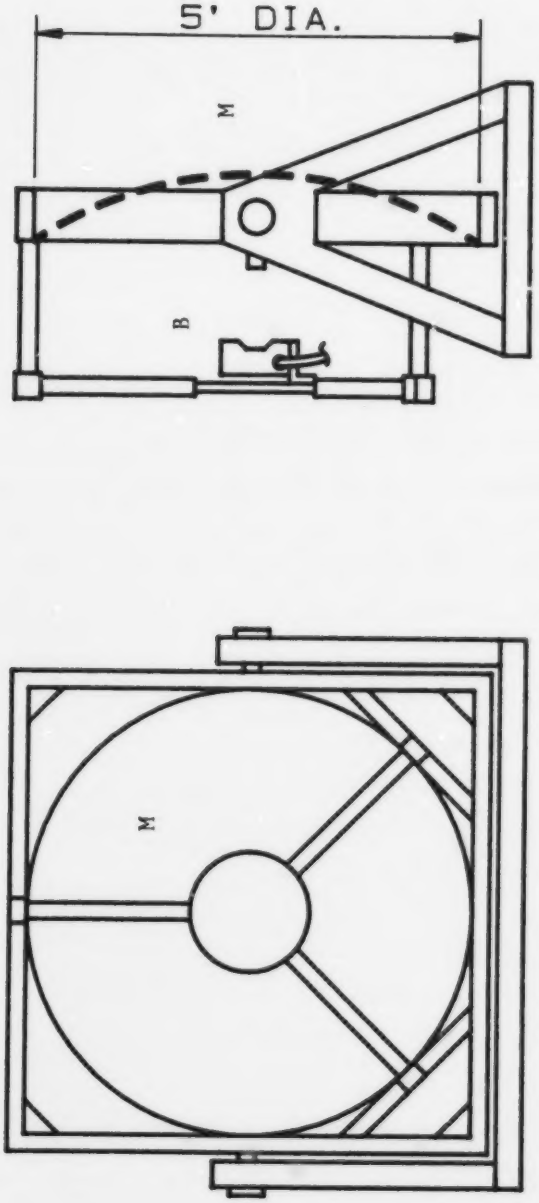


FIGURE 1 - Front view and side view of the transmitter optics.
B - flat-plate blackbody; M - parabolic mirror

3.0 CALIBRATION METHOD

3.1 Determination of the Calibration Factor

Figure 2 illustrates the difference between the ray tracing of the local and distant sources. The local source is imaged on the entrance aperture F_1 by two off-axis parabolic mirrors. The distant source is imaged on F_1 by the 17" Newtonian telescope. The optical system of the instrument forms an image of either the local source or the distant mirror-blackbody combination at a position in front of the detector condensing mirror F_2. A field-limiting exit aperture is placed at this point to restrict the intensity transmitted by the local blackbody. The image of the distant source is, however, smaller than the field-limiting aperture. The calibration factor can thus be expressed as a ratio of the sizes and radiances of both images as described below.

When a source is imaged by an optical system, the image may be treated as a secondary source of radiation. Radiance is the radiant flux per unit solid angle per unit area (W/cm^2-sr) emitted from an object or an image. According to Smith (Ref. 4), for any aplanatic optical system (free of coma and spherical aberration) and for a Lambertian source, the radiance of the image is equal to that of the object multiplied by the transmission of the system,

$$N' = TN. \qquad [1]$$

This fundamental relationship in radiometry is discussed in detail in Ref. 4.

Applying this result to the calibration problem, we find that the image radiance N'_{mb} of the distant mirror-blackbody source combi-

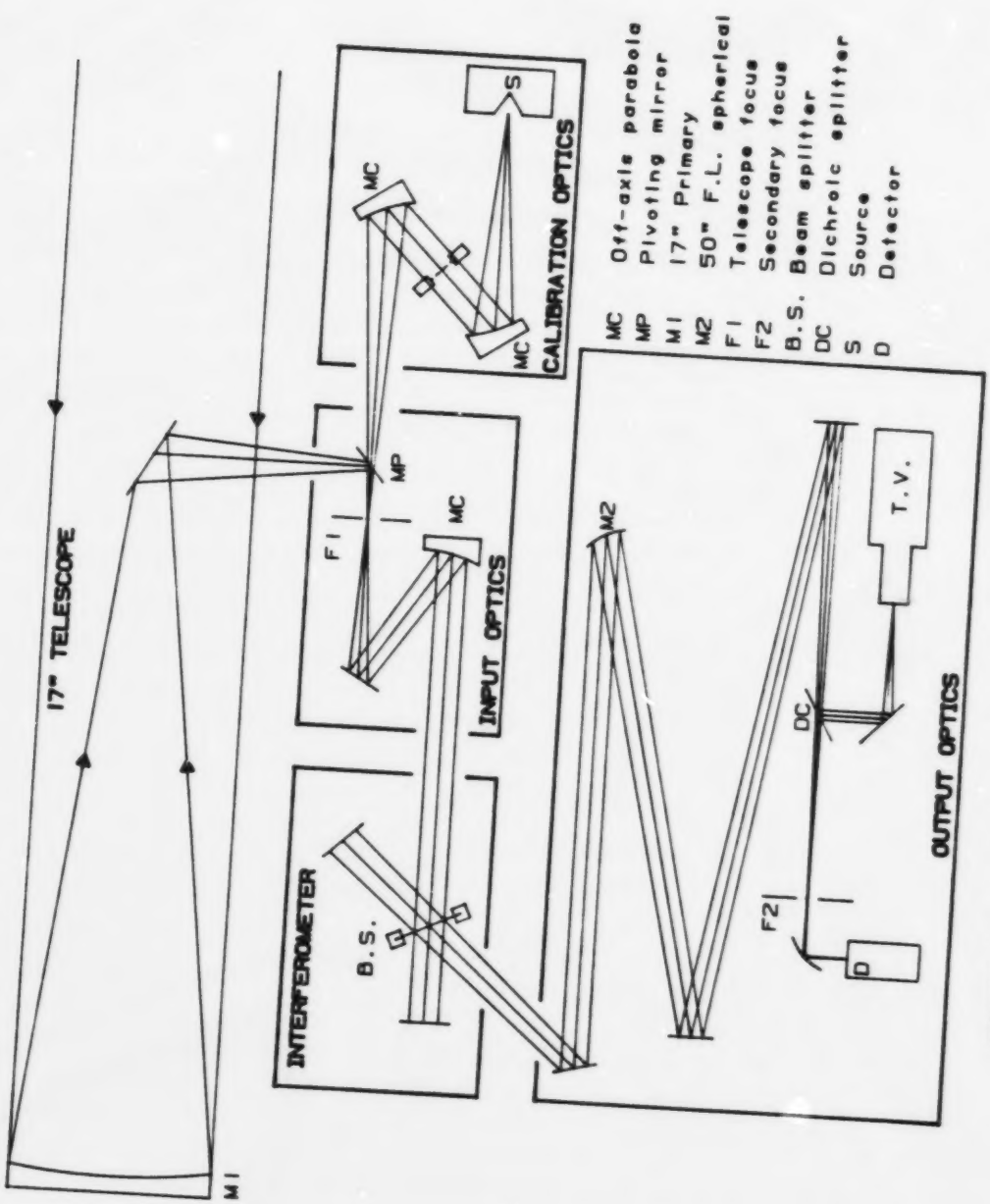


FIGURE 2 - Schematic representation of the receiver optics

nation at the second focus (F_2) of the system is given by

$$N'_{mb} = T_{sys} \cdot R^3 \cdot T_{atm} \cdot N_{mb} \qquad [2]$$

where

N_{mb} = radiance of the distant mirror-source assembly

T_{sys} = transmission of the system from F_1 to F_2

R = reflectance of mirrors

T_{atm} = atmospheric transmission.

Similarly, we find that for the local source the image radiance N'_{loc} is

$$N'_{loc} = T_{sys} \cdot R^2 \cdot N_{loc}, \qquad [3]$$

where N_{loc} is the radiance of the local blackbody source given by the Planck equation

$$N_{loc} = \frac{1}{\pi} \frac{c_1}{\lambda^5 (e^{c_2/\lambda\tau} - 1)}, \qquad [4]$$

where λ is the wavelength and τ is the temperature of the blackbody. C_1 and C_2 are equal to 3.742×10^{-12} W-cm^2 and 1.439 cm -K respectively.

In order to evaluate the calibration factor, the total power reaching the detector from each source has to be compared. For the local source, the power P_{loc} is given by

$$P_{loc}(\text{watts}) = N'_{loc} \cdot A_{ap} \cdot \Omega_{sys} \qquad [5]$$

where A_{ap} is the area of the field-limiting aperture, and Ω_{sys} is the solid angle subtended from the image by the clear aperture of the optical system.

In eq. 5 the image is assumed to overfill the aperture. For the distant source, the power reaching the detector is given by

$$P_d(\text{watts}) = N'_{mb} \cdot A_d \cdot \Omega_{sys} \qquad [6]$$

where A_d is the image area of the distant source which depends on the transmitter-receiver distance and on the system magnification.

Knowing that the distant source produces an image of diameter

$$h_d = \frac{D_{mir}}{d} \cdot \frac{f_1 f_3}{f_2} \qquad [7]$$

it follows that the image area is given by

$$A_d = \frac{A_m}{d^2} \left(\frac{f_1 f_3}{f_2}\right)^2 \qquad [8]$$

where D_{mir}, A_m are the diameter and the area of the distant source-mirror (60-in); d is the transmitter-receiver distance (5.7 km); f_1, f_2 and f_3 are the focal lengths of the receiving telescope (m1), the interferometer's collimator (MC) and the condenser (M2), respectively.

Ratioing eq. 5 and 6 and substituting eqs. 2, 3 and eq. 8 yields

$$\frac{P_d}{P_{loc}} = \frac{R}{d^2} \cdot \frac{A_m}{A_{ap}} \left(\frac{f_1 f_3}{f_2}\right)^2 \cdot \frac{N_{mb}}{N_{loc}} \; T_{atm}, \qquad [9]$$

and the calibration factor is thus defined as

$$K(\lambda) = \frac{R}{d^2} \frac{A_m}{A_{ap}} \left(\frac{f_1 f_3}{f_2} \right)^2 \frac{N_{mb}}{N_{loc}} . \qquad [10]$$

Once the calibration factor is determined, the transmission of the atmosphere is given by

$$T_{atm}(\lambda) = \frac{1}{K(\lambda)} \frac{P_d(\lambda)}{P_{loc}(\lambda)} , \qquad [11]$$

where $P(\lambda)$ is the measured spectral power at wavelength λ.

The only remaining quantity which is not defined in eq. 10 is the radiance of the distant source N_{mb}. The derivation of N_{mb} is discussed in Section 3.2.

3.2 Radiance of the Distant Source

An ideal IR source would consist of a perfect blackbody (Lambertian radiator) situated exactly at the focus of a diffraction limited collimating mirror. Let us assume that the f-number of the mirror is high enough to neglect the cosine θ dependence of the blackbody radiator. In this case an observer situated close to the output beam of this collimator will see a radiance uniformly distributed over the entire mirror. By using a simple ray tracing construction (Fig. 3a), it is evident that the mirror acts as a secondary source of blackbody radiation (classical result). Thus the radiance of an ideal mirror-blackbody source combination is given by the Planck radiation law times the reflectance R of the collimating mirror, i.e.,

$$N_{mb} = R \cdot \left(\frac{1}{\pi} \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)}\right). \qquad [12]$$

Substituting eqs. 4 and 12 in eq. 10 yields a simplified expression for the calibration constant

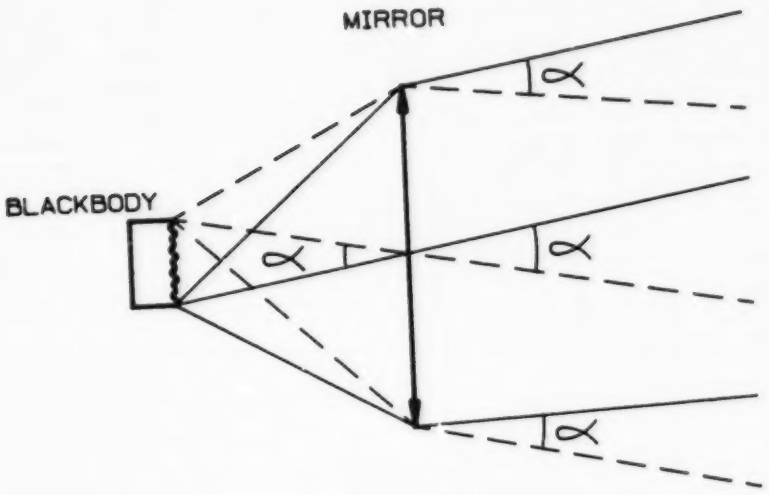
$$K = \frac{R^2}{d^2} \frac{A_m}{A_{ap}} \left(\frac{f_1 f_3}{f_2}\right)^2. \qquad [13]$$

In eq. 13 both the local and distant blackbodies are assumed to have the same temperature.

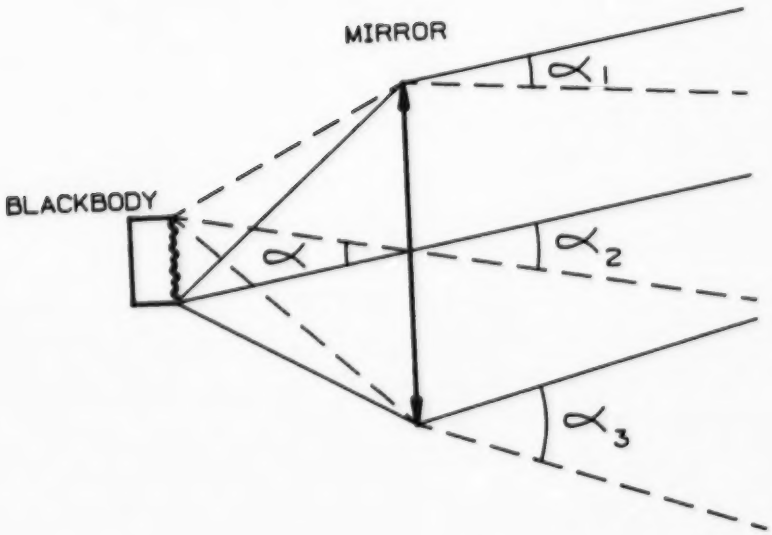
If the mirror-blackbody assembly is not optically perfect, an observer situated close to the output beam of this collimator will see an irregular distribution radiance across the mirror (Fig. 3b). This non-uniformity may due to an imperfect mirror figure, misalignment of the blackbody relative to the mirror or the fact that mirror reflectance is a function of incidence angle for small f number. To take into account such imperfections, the radiance of a real blackbody-mirror source may be redefined as

$$N_{mb} = R \cdot \left(\frac{1}{\pi} \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)}\right) \cdot Q \qquad [14]$$

where Q (< 1) is defined here as the quality factor. The assumption behind eq. 14 comes from the fact that the receiver, situated far from the source, detects only the average of the radiance emitted at the mirror's surface. It follows from eq. 14 that the calibration factor is given by



a) Ideal case, uniform radiance



b) Real case, non-uniform radiance

FIGURE 3 - Ray tracing construction for the blackbody-mirror source assembly

$$K = \frac{R^2}{d^2} \frac{A_m}{A_{ap}} \left(\frac{f_1 f_3}{f_2} \right)^2 \cdot Q \qquad [15]$$

assuming again the same temperature for both sources.

Despite the fact that the calibration equation 15 of the transmissometer is simple, the accuracy with which the transmittance can be known depends mainly on the accuracy with which the quality factor is known. The next chapter discusses the experimental determination of the Q factor.

4.0 DETERMINATION OF THE Q FACTOR

In Ref. 3, the Q factor of a source was determined by mounting a radiometer near the front of the collimating mirror. The local radiance of the source assembly was measured normal to its axis at many points. An intensity map was then generated and the quality factor was found to be 0.81 ± 0.03. In the following, we present a method developed at DREV to determine the Q factor, which is simpler and more accurate than the method described in Ref. 3.

4.1 Principle of the Method

The present method is based on a direct comparison between the signal (at the receiver) produced by the mirror-blackbody assembly and the signal of the same blackbody alone. The experimental setup of the sources is showed in Fig. 4.

Using the results given in the preceding chapters, for the distant source, the power reaching the detector of the receiver is given by (see. eq. 6)

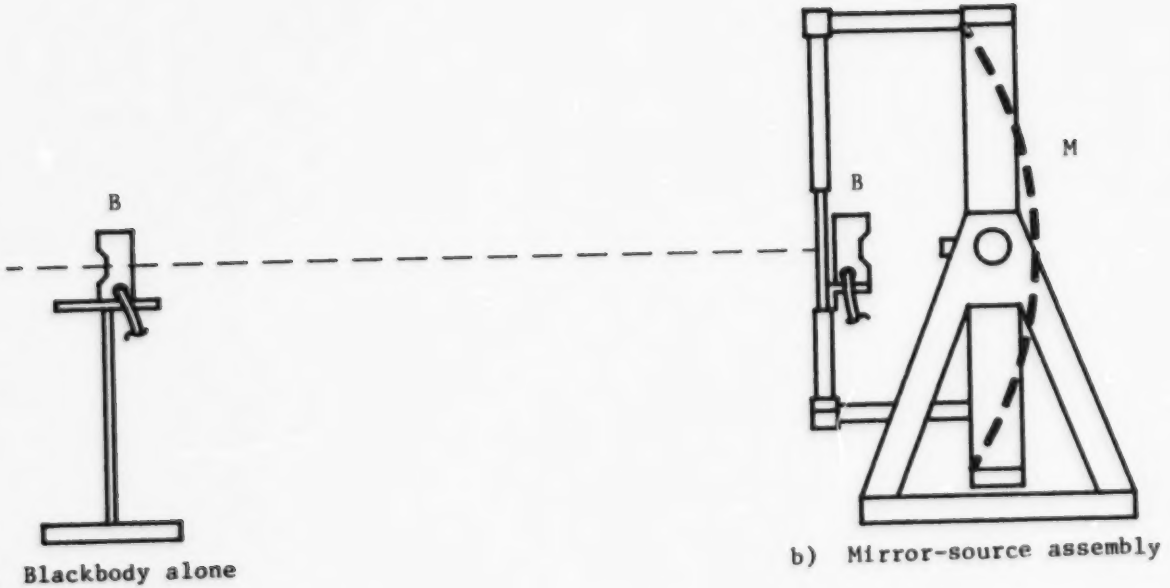


FIGURE 4 - Experimental setup of the sources
B - flat-plate blackbody, M - 5' parabolic mirror

Blackbody alone:

$$P_b = N'_b \cdot A'_b \cdot \Omega_{sys} \qquad [16a]$$

Mirror-blackbody assembly:

$$P_{mb} = N'_{mb} \cdot A'_m \cdot \Omega_{sys} , \qquad [16b]$$

where

$$N'_b = (T_{sys} \cdot R^3 \cdot T_{atm}) \left(\frac{1}{\pi} \frac{c_1}{\lambda^5 (e^{\,c_2/\lambda T} - 1)}\right)$$

$$A'_b = \frac{A_b}{d^2}\left(\frac{f_1 f_3}{f_2}\right)^2$$

and

$$N'_{mb} = (T_{sys} \cdot R^3 \cdot T_{atm})\left(\frac{1}{\pi} \frac{c_1}{\lambda^5 (e^{\,c_2/\lambda T} - 1)}\right) R \cdot Q$$

$$A'_m = \frac{A_m}{d^2}\left(\frac{f_1 f_3}{f_2}\right)^2 .$$

(A_b and A_m are respectively the effective areas of the blackbody and of the mirror). Ratioing eq. 16a and eq. 16b leads to the simple expression

$$\frac{P_b}{P_{mb}} = \frac{A_b}{A_m} \cdot \frac{1}{R \cdot Q}$$

or

$$Q \cdot R = \frac{P_{mb}}{P_b} \cdot \frac{A_b}{A_m}, \qquad [17]$$

which is the Q factor (times the reflectance of the parabolic mirror) in terms of signals ratio and areas ratio.

4.2 Preliminary Results

In order to determine the Q factor, three sets of three transmission spectra were recorded at very low resolution (75 cm^{-1}, degraded resolution) over the 5.7-km path during stable atmospheric conditions. The first spectrum was produced by the 2" x 2" flat-plate square blackbody at a temperature of 700°C. The second spectrum is the background in the absence of the blackbody, recorded immediately after the blackbody spectrum. The third transmission spectrum has the mirror-blackbody assembly as the source.

Figure 5 shows the relative contribution of the background to the blackbody spectrum. Figures 6 and 7 are respectively the transmission spectrum of the blackbody alone (background subtracted) and of the mirror-blackbody assembly, while Fig. 8 is the superposition of both curves, using an appropriate scaling factor. It is important to note that the shapes of the curves are similar, especially in the 2400-3000 cm^{-1} region. Figure 9 summarizes the results of signal ratio P_b/P_{mb} for the three sets of measurements and shows very good reproducibility. However, the 4000-5000 cm^{-1} region has to be excluded from the analysis because in that part of the spectrum the contribution of sun reflection from the background can change significantly between successive measurements, and consequently lead to erroneous results. In this region, the signal ratio P_b/P_{mb} did in fact give large variations as shown in Fig. 10.

In the region of interest (2400-3000 cm^{-1}), the mean value of the ratio is

$$\frac{P_b}{P_{mb}} = 2.30\ (\pm\ 0.05) \times 10^{-3}.$$

Combining this result with eq. 17 and with $A_m = 1.636 \times 10^4$ cm^2 (Ref. 3) and $A_b = 25.81$ cm^2 (2" x 2") gives

$$R \cdot Q = 0.686 \pm 0.02,$$

and assuming that $R = 0.97 \pm 0.02$ (as in Ref. 3) we have

$$Q = 0.707 \pm 0.03.$$

The present method gives a value for Q slightly lower than that from the method described in Ref. 3. After determining the Q factor in the laboratory, the 5-ft parabolic mirror and its holder were moved to the transmitter site. This large mirror has a substrate thickness of only 1/8 in and is consequently quite flexible. Thus it is possible that transportation has significantly degraded the optical surface by stressing the mirror mount. Also the physico-chemical state of the mirror surface may have degraded slightly due to cleaning before the present measurements.

In order to make sure that our field measurement method gives accurate results (without systematic error), we have to measure the effective area of the flat-plate blackbody and then validate the precision of the method with a perfect collimating system (diffraction-limited collimator, Q = 1). After which, a quantitative comparison of those methods (laboratory and field) would be appropriate.

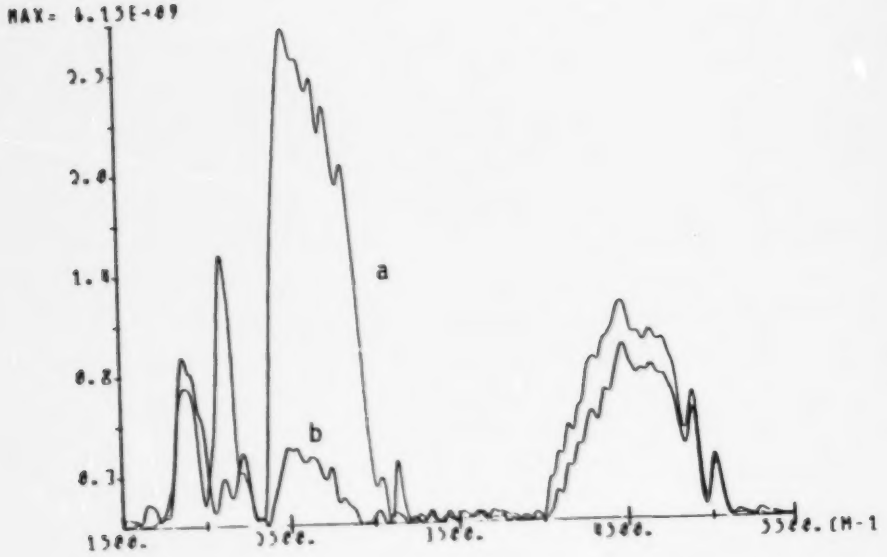


FIGURE 5 - a) Transmission spectrum of the blackbody and background
b) Background spectrum

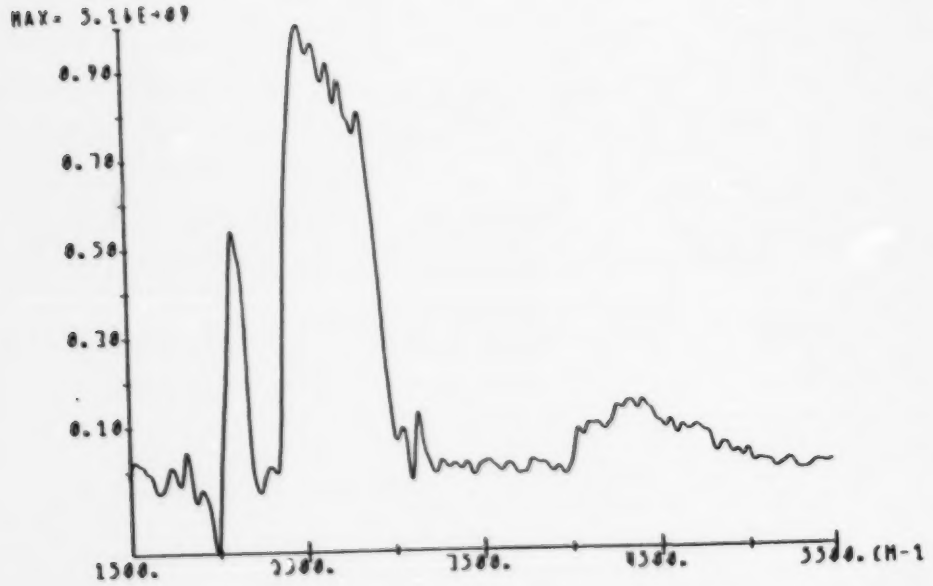


FIGURE 6 - Transmission spectrum of the blackbody without background

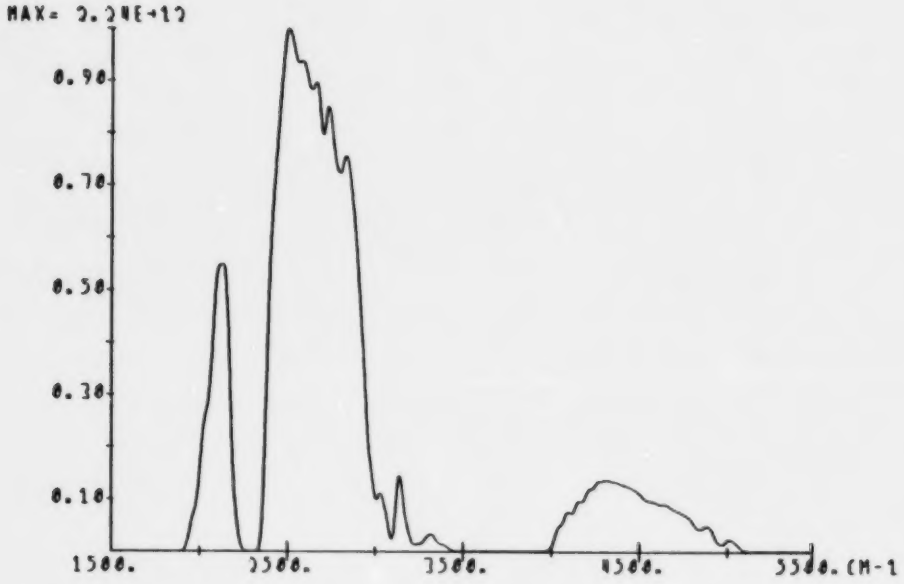


FIGURE 7 - Transmission spectrum of the mirror-blackbody assembly

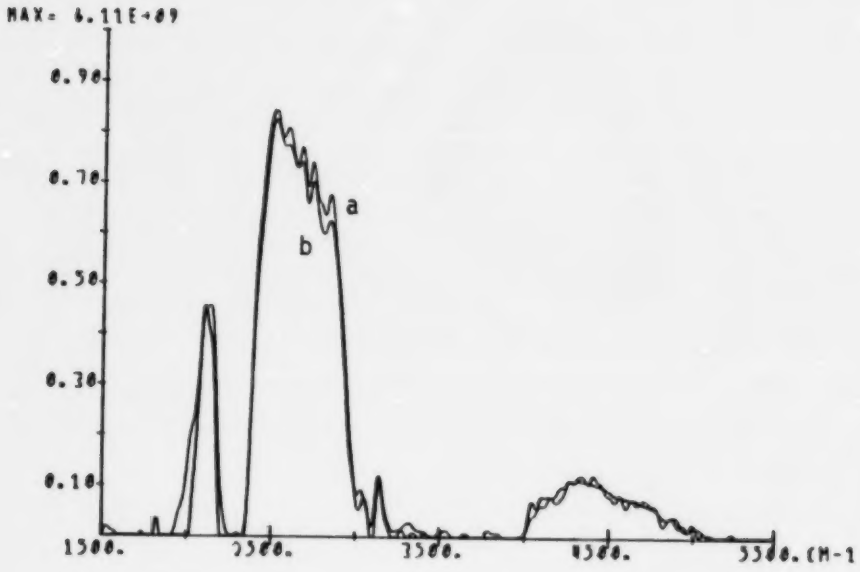


FIGURE 8 - Comparison of transmission spectrum:
a) blackbody alone
b) source assembly

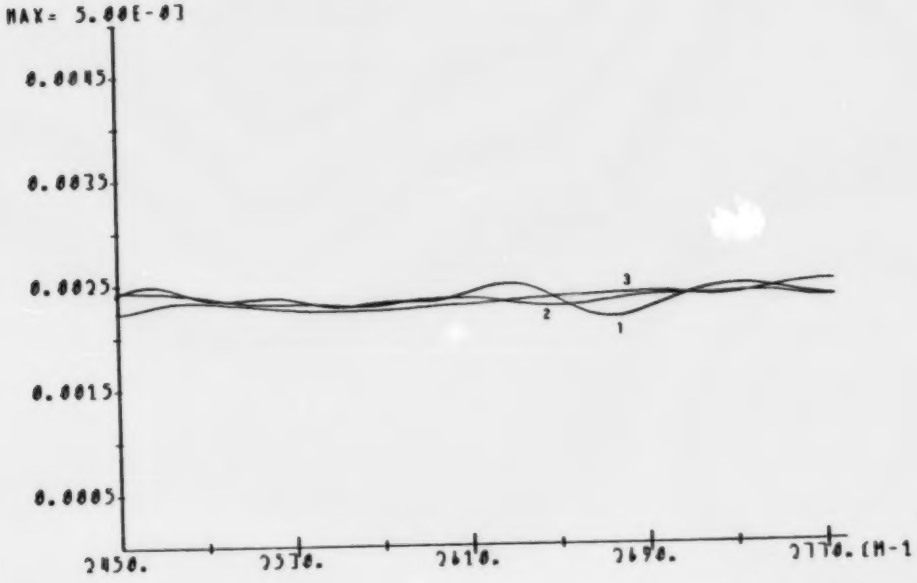


FIGURE 9 - Signal ratio, P_b/P_{mb} vs wavenumber in the 2400-3000 cm^{-1} region for three measurements

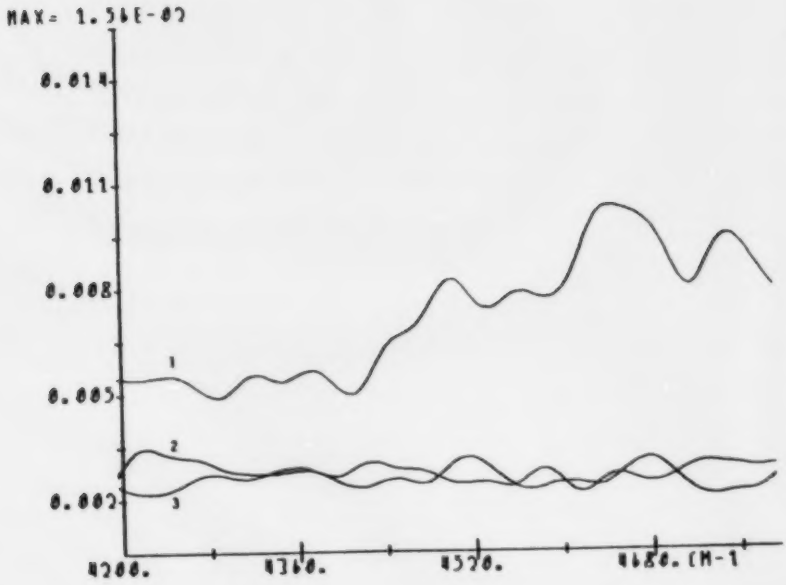


FIGURE 10 - Signal ratio, P_b/P_{mb} vs wavenumber in the 4000-5000 cm^{-1} region for three measurements

5.0 CONCLUSION

A method of calibration for the Fourier Interferometric Transmissometer (FIT) has been presented. Atmospheric transmittance is determined by obtaining the ratio of the distant source signal to the local reference signal and subsequently correcting it by a calibration factor.

Accuracy of atmospheric transmittance measurements is a function of several factors such as blackbody radiance, effective collimating-mirror area, mirror reflectance and emissivity. However, the most important difficulty lies in the evaluation of the quality factor associated with the degree of collimation of the distant source-mirror assembly. The method to determine Q proposed in this report is based on a direct comparison between the signal produced by the mirror-blackbody assembly and the signal of the same blackbody alone. The precision of the method seems to be limited by the blackbody stability (in temperature) between successive measurements. Stability tests have indicated that a ± 4°C variation of the 2-in square blackbody temperature is typical. Evaluation of the corresponding radiance fluctuation at T=700°C and λ=4.1 μm leads to an accuracy better than ± 2% for Q. Preliminary results agree well with this estimate and show that the reproducibility of measurements (without the uncertainty of mirror reflectance) is roughly ± 2%. We believe that this procedure should be incorporated in any transmissometer calibration routine in order to evaluate or verify the collimation quality ($Q \leq 1$) of the target source. The precision of Q, combined with the uncertainties of other factors mentioned above, should give an accuracy of ± 5% on atmospheric transmittance measurements.

Although the calibration method is theoretically quite simple, its application may pose some experimental difficulties. Great care must be taken in the alignment of the optical system in order to co-axially align the calibration optics with the receiver optics. Without this precise alignment, clipping problems related to the small dimension of the detector can lead to erroneous atmospheric transmittance spectra.

6.0 ACKNOWLEDGEMENTS

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